

# Ultra-High Energy Cosmic Rays and Neutron-Decay Halos from Gamma Ray Bursts

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**Abstract.** Simple arguments concerning power and acceleration efficiency show that ultra-high energy cosmic rays (UHECRs) with energies  $\gtrsim 10^{19}$  eV could originate from GRBs. Neutrons formed through photo-pion production processes in GRB blast waves leave the acceleration site and travel through intergalactic space, where they decay and inject a very energetic proton and electron component into intergalactic space. The neutron-decay protons form a component of the UHECRs, whereas the neutron-decay electrons produce optical/X-ray synchrotron and gamma radiation from Compton-scattered background radiation. A significant fraction of galaxies with GRB activity should be surrounded by neutron-decay halos of characteristic size  $\sim 100$  kpc.

## 1 Introduction

Gamma-ray bursts produce enough power within the Greisen-Zatsepin-Kuzmin (GZK) photopion production radius to power the UHECRs [1,2,3]. Stochastic gyroresonant acceleration of protons and ions by turbulence generated in relativistic blast waves can accelerate particles to ultra-high energies [4]. Energetic neutrons are formed by photopion interactions of accelerated hadrons with nonthermal synchrotron radiation in GRB blast waves. The neutrons travel through intergalactic space and decay, and the neutron-decay electrons form synchrotron and Compton halos around galaxies with GRB activity. The discovery of neutron-decay halos around galaxies with vigorous star-forming activity will provide strong evidence for a GRB origin of the UHECRs [3].

## 2 GRB Origin of UHECRs: Power and Acceleration

As a consequence of Beppo-SAX results, we now know that GRBs are extragalactic and originate from sources with a broad distribution of redshifts and mean redshift  $\bar{z} \approx 1$ . Beppo-SAX has a much smaller field-of-view than BATSE, but triggers on nearly the same sample of long-duration ( $t_{50} \gtrsim 1$  s) GRBs. If UHECRs originate from GRBs, then the product of the UHECR energy density  $u_H$  and the characteristic source volume  $V$  is equal to the product of the GRB power  $L_{GRB}$ , the loss time from the source volume, and the efficiency  $\epsilon$  to convert GRB energy into UHECRs. For protons with energies  $\gtrsim 10^{20}$  eV, the GZK radius is  $\sim 140$  Mpc [5]. Thus the loss time  $t_{p\gamma} \cong 140 \text{ Mpc}/c \cong 1.4 \times 10^{16}$  s. Hence  $u_H \cong \epsilon f L_{GRB} t_{p\gamma} / V$ , where  $f$  is a factor that takes into account present

day star-formation activity compared with that occurring at  $\bar{z}$ . If  $\bar{z} = 1$ , then  $f \cong 1/6$ .

Let  $\bar{d} = 10^{28} d_{28}$  cm represent the average luminosity distance to observed GRBs, so that  $V \cong 4\pi\bar{d}^3/3$ . The power of GRBs into the volume  $V$  is given by the typical GRB energy  $E_{GRB}$  multiplied by the GRB rate. BATSE is sensitive to GRBs with peak fluxes  $\phi \gtrsim 10^{-7} \phi_{-7}$  ergs cm $^{-2}$  s $^{-1}$ . The observed mean duration of the long duration GRBs is  $t_{dur} = 30t_{30}$  s. Thus  $E_{GRB} \approx 4\pi\bar{d}^2 \cdot 10^{-7} \phi_{-7} \cdot 30t_{30}(1+\bar{z})/(0.1\eta_{-1}) \approx 4 \times 10^{52} d_{28}^2 \phi_{-7} t_{30} (1+\bar{z})/\eta_{-1}$  ergs, where  $\eta = 0.1\eta_{-1}$  is the efficiency for transforming the GRB explosion energy into  $\gamma$  rays in the Beppo-SAX and BATSE energy bands. The long-duration GRBs occur at a rate of  $\approx 1/(t_{day} \text{ day})$ , with  $t_{day} \approx 1$ , so that  $L_{GRB} \approx 4 \times 10^{47} d_{28}^2 \phi_{-7} t_{30} (1+\bar{z})^2/(\eta_{-1} t_{day})$  ergs s $^{-1}$ . We therefore find that

$$u_{UH} \text{ (ergs cm}^{-3}\text{)} \approx 1.5 \times 10^{-21} \frac{k \epsilon f \phi_{-7} t_{30} (1+\bar{z})^2}{\eta_{-1} t_{day} d_{28}}. \quad (1)$$

The factor  $k$  represents the energy released by the dirty and clean fireballs which do not trigger the BATSE detector. Detailed calculations within the context of the external shock model show that  $k \approx 3$  [5].

Observations show that  $u_{UH} \cong 10^{-20}$  and  $2 \times 10^{-21}$  ergs cm $^{-3}$  for cosmic rays with  $E \gtrsim 10^{19}$  eV and  $10^{20}$  eV, respectively. (For protons with energies  $\gtrsim 10^{19}$  eV,  $t_{p\gamma} \cong 1000$  Mpc/c.) If an efficient mechanism for converting the energy of the relativistic outflows into UHECRs exists, then there is sufficient power in the sources of GRBs to power the UHECRs. Detailed calculations [3,6,7] verify this result.

Particle acceleration in GRB blast waves must satisfy the Hillas [8] condition for UHECR production, which requires that the Larmor radius be smaller than the characteristic size of the acceleration region. For GRB blast waves, this size is the blast-wave width. Hence the particle Larmor radius  $r_L = (Am_p c^2 / ZeB)$  ( $\gamma_{max}/\Gamma$ )  $< \Delta' = f_\Delta x / \Gamma$ , where  $\gamma_{max}$  is the maximum particle Lorentz factor measured in the explosion frame,  $\Gamma = 300\Gamma_{300}$  is the blast wave Lorentz factor,  $\Delta'$  is the comoving blast wave width,  $f_\Delta \cong 1/12$  from hydrodynamics, and  $x = 10^{16} x_{16}$  cm is the location of the blast wave from the explosion center. The blast-wave magnetic field  $B \cong \sqrt{32\pi e_B n_{ISM} m_p c^2} \Gamma \cong 0.4 \sqrt{e_B n_{ISM}} \Gamma$  G is defined by a magnetic-field parameter  $e_B (< 1)$ , and the term  $n_{ISM}$  is the particle density of the surrounding medium. Thus

$$E_{max} = Am_p c^2 \gamma_{max} = ZeB f_\Delta x \simeq 3 \times 10^{19} Z \sqrt{e_B n_{ISM}} \left( \frac{f_\Delta}{1/12} \right) x_{16} \Gamma_{300} \text{ eV}. \quad (2)$$

A wide range of parameter values can satisfy the Hillas condition for accelerating UHECRs by stochastic acceleration through gyroresonant interactions with MHD turbulence in the blast wave fluid [4,9]. The Alfvén speed  $v_A$  in the relativistic shocked fluid is also relativistic (naively using the nonrelativistic expression gives  $v_A/c \cong \sqrt{2e_B \Gamma}$ , resulting in an acceleration rate that is much more rapid for second-order than for first-order processes [9,10].

### 3 Neutron-Decay Halos

Accelerated protons and ions interacting with nonthermal synchrotron radiation in the blast wave will produce neutrons through the process  $p + \gamma \rightarrow n + \pi^+$ . The neutrons, unbound by the magnetic field in the blast wave, leave the acceleration site with Lorentz factors  $\gamma_n = 10^{10} \gamma_{10}$ , with  $0.1 \lesssim \gamma_{10} \lesssim 100$ . The neutrons decay on a timescale  $\gamma_n t_n \simeq 3 \times 10^5 \gamma_{10}$  yr, where the neutron  $\beta$ -decay lifetime  $t_n \simeq 900$  s. The neutrons travel a characteristic distance  $\lambda_n \simeq 90 \gamma_{10}$  kpc before they decay and inject highly relativistic electrons and protons into intergalactic space. Approximately 1% of the energy of a GRB explosion with  $10^{54} E_{54}$  ergs is deposited into highly relativistic neutrons when  $E_{54} \approx 1$  [3]. The neutron-decay electron halo surrounding a galaxy from a single GRB reaches a maximum power of  $L_{halo} \approx 0.01 \times \mathcal{F} 10^{54} E_{54} (m_e/m_p) / (\gamma_n t_n) \approx 10^{36} E_{54} \mathcal{F} / \gamma_{10}$  ergs s<sup>-1</sup>. Detailed calculations show that  $\mathcal{F} \approx 0.1$  [3]. The neutron-decay protons become part of the UHECRs. GRB explosions with  $E_{54} \gtrsim 0.2$  occur at a rate of about once every 5 Myrs per L\* galaxy, implying that  $\sim (5-10) \gamma_{10} \%$  of L\* galaxies should display a neutron-decay halo at maximum power. If GRB emission is beamed, a larger fraction of galaxies will display proportionally weaker halos.

The beta-decay electrons radiate nonthermal synchrotron emission and Compton scatter CMB photons to high energies. The maximum synchrotron frequency is  $\nu \sim 3 \times 10^{20} B(\mu\text{G}) \gamma_{10}^2$  Hz, where  $B(\mu\text{G})$  is the mean magnetic field in the region surrounding the galaxy in  $\mu\text{G}$ . The halo will display a cooling synchrotron spectrum at optical and soft X-ray energies. The electromagnetic cascade formed by the Compton-scattered  $\gamma$  rays terminates when the  $\gamma$  rays are no longer energetic enough to pair produce with the diffuse radiation fields. The relative intensity of the synchrotron and Compton components depends on the magnitude of  $B(\mu\text{G})$ . The best prospect for discovering neutron-decay halos is by optical observations of field galaxies that display active star formation [3].

We also note that the emission of nonthermal synchrotron and Compton radiation from photopion processes by UHECRs traveling through intergalactic space will produce a nonthermal component of the diffuse radiation background, irrespective of the sources of UHECRs.

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